HYDRODYNAMIC AND MORPHOLOGIC ANALYSIS OF DESIGN ALTERNATIVES FOR PONCE DE LEON INLET, FL

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Abstract: Despite years of engineering efforts, studies, and maintenance by USACE, Ponce de Leon Inlet, FL still suffers from severe shoaling and channel migration leading to hazardous navigation and mechanical stress on the north jetty. To help remove the stalemate over re-engineering the inlet, the present study applied the fully-integrated Coastal Modeling System (CMS) to determine the redesign that best improves navigation, alleviates structural stress on the north jetty, and reduces shoaling of the south spit. Comparison of net morphologic changes, normalized volume changes within 15 sub-domains, and hydrodynamic changes during both spring and neap tides allowed the favored designs from a 3-month run to be modeled for a 10-month run, to include fall and winter storm events. Taken in total with the three areas of concern in mind, the South Jetty Extension with Submergent Spur, Hard Bottom, and Channel Redesign was considered the optimal candidate modeled in this study.

Background

Ponce de Leon is one of 154 inlets federally-maintained by the U.S. Army Corps of Engineers (USACE). In 1993, the Coastal and Hydraulics Laboratory (CHL) of the U.S. Army Engineer Research and Development Center (ERDC) initiated the Coastal Inlets Research Program (CIRP) to study the complex morphologic and hydrodynamic changes of coastal inlets, which occur on a variety of temporal and spatial scales, and to develop technology specific for addressing operation and maintenance concerns. CIRP's initial field investigation involved long-term (1995-1997) comprehensive monitoring to generate a baseline analysis of physical conditions and establish an available archive of data. Ponce Inlet was chosen for numerous reasons, chief of which was the engineering concern that persisted since stabilization of the inlet in 1972 by a weir-jetty system and subsequent closure of the weir in 1984 (Howell 1996; Harkins et al. 1997; King et al. 1999).

Closing of the weir was intended to be a temporary event leading to realignment of the shorelines and channel. Prior to reopening the weir, a feasibility study using numerical (Taylor et al. 1996a, 1996b) and physical modeling (Harkins et al. 1997) was undertaken to assess modification alternatives. Results suggested that a 305 m dogleg extension of the south jetty and a 244 m landward extension of the north jetty should alleviate the hazardous navigation conditions, shoreline erosion, and channel instability (Taylor et al. 1996b; Srinivas and Taylor 1999). The report also

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14. ABSTRACT
Despite years of engineering efforts, studies, and maintenance by USACE, Ponce de Leon Inlet, FL still suffers from severe shoaling and channel migration leading to hazardous navigation and mechanical stress on the north jetty. To help remove the stalemate over re-engineering the inlet, the present study applied the fully-integrated Coastal Modeling System (CMS) to determine the redesign that best improves navigation, alleviates structural stress on the north jetty, and reduces shoaling of the south spit. Comparison of net morphologic changes, normalized volume changes within 15 sub-domains, and hydrodynamic changes during both spring and neap tides allowed the favored designs from a 3-month run to be modeled for a 10-month run, to include fall and winter storm events. Taken in total with the three areas of concern in mind, the South Jetty Extension with Submergent Spur, Hard Bottom, and Channel Redesign was considered the optimal candidate modeled in this study.

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stated that a detailed analysis from a fully-coupled hydrodynamic/sediment transport model was necessary for a complete prediction of morphologic changes.

Upon announcement of the intended changes in design slated for 2004, the surfing community expressed concern that a south jetty extension would affect the surfing break at New Smyrna Beach (south of the inlet). The County of Volusia-Inlet and Port Authority district asked USACE Jacksonville District to redesign for a parallel south jetty. However, details of the impacts from a parallel design were not included in the 1996 feasibility study. Additionally, concern for negative impacts on circulation within the estuary west of the inlet and the probability of increased downdrift erosion prompted the extension project to be halted until USACE could provide more substantiated results than those presented in the feasibility study. Although the landward extension of the north jetty to revet the north spit was successfully completed, the south jetty extension was cancelled from the 2007 Volusia County budget. The present study sought to provide more detailed, predictive models of design alternatives that fully integrate wind, waves, currents, sediment transport, and morphology change to remove the re-engineering stalemate.

STUDY SITE

Ponce de Leon Inlet is located in the middle of Volusia County along the east coast of Florida (29°05'N, 80°55'W) with a shoreline azimuth of 326° (Figure 1). Two offset jetties were constructed in 1967-72 to stabilize the inlet (Figure 2). The north jetty is a 152 m long concrete sheet pile, followed by a 549 m long weir section (now armor stones), and another 549 m of rubble mound (total 1250 m). Recent landward extension to revet the eroding north spit (west of jetty) makes the length 1868 m. The south jetty, designed as a curved, rubble mound structure 1243 m long, is now 120 m. Although the navigation channel was designed and maintained at a depth of 4.6 m and a width of 61 m (Figure 2), shoaling has resulted in a shifting of the channel leaving behind a minimum depth of < 1 m in places. Presently, the navigation channel is aligned with and adjacent to the north jetty (light blue in Figure 1) and high resolution Scanning Hydrographic Operational Airborne LIDAR (Light Detecting and Ranging) Surveys (SHOALS) indicate depths of 11.5 m.

Offshore, mean tidal range is 1.0 m (spring is 1.3 m). Inside the inlet, mean range is 0.8 m. Tidal harmonics indicate M2 dominance (amplitude 0.45 m near the inlet). During a typical tidal cycle, peak currents in the throat are 1.0 m/s, reaching 1.3 m/s during spring tides. Zarillo and Militello (1999) observed significant wave heights averaging 0.9 m over the ebb shoal reducing to 0.6 m in the inlet. The average wave period was 8 to 9 s, with maximum of 14 s. A comparison of all research and year-long trends of offshore buoys indicates dominant wave direction is from the northeast (NE). The fully developed, bifurcated flood shoal suggests a flood-dominant system, although analysis of the maximum current velocities and duration during ebb and flood indicates spatial and temporal variability in peak currents. Average wind speeds are 4 to 6 m/s with dominant directions from NNE and SSE.

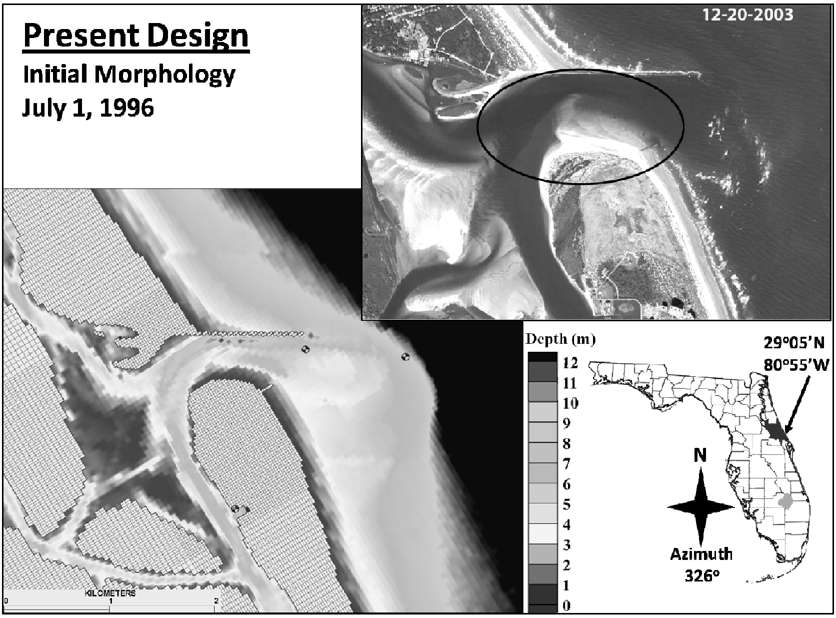

Figure 1. Ponce de Leon Inlet, FL study site. (FDEP, 2004 DOQQ, original scale 1:12,000)

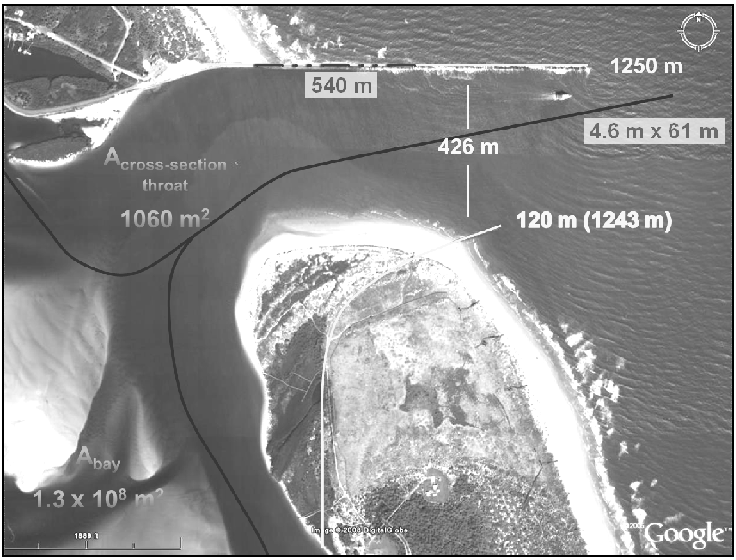

Figure 2. Aerial image with '67 design parameters. (Google Earth, 2006, original scale 1:12,000)

Coastal Modeling System (CMS)

CMS was used to develop 2D depth-integrated models predicting the hydrodynamic and morphologic evolution of design alternatives. CMS is a coupled, process-based hydrodynamic/wave/sediment transport/morphodynamic model developed and supported through CHL/CIRP and interfaced through the Surface-water Modeling System (SMS) developed by Aquaveo, Inc. CMS-Flow is a time dependent, 2D finite volume circulation and morphology model that calculates water surface elevation (WSE), u and v of the current, and sediment transport on a rectilinear grid of variable cell sizes (Militello et al. 2004). Within CMS-Flow, three sediment transport formulations are available for calculating transport rates and resultant bottom elevation changes (Buttolph et al. 2006). The model can be forced at the boundaries by flow-rate (river), WSE, WSE and velocity (extracted from a regional model), or tidal constituents. CMS-Flow can be fully-coupled with CMS-Wave at user specified intervals. CMS-Wave is based on the Wave-Action Balance Equation with Diffraction (WABED) model approximating both diffraction and reflection. It is a half-plane, steady-state, spectral, finite-differencing model capable of simulating shoaling, refraction, breaking, and growth of waves due to wind. CHL/CIRP continues support through improving calculation of radiation stresses applicable to wave-current interactions (Demirbilek et al. 2007) and upgrades to the wave model including bed friction, runup, variable cell size, and topographic modification for rubble mound, breakwaters, and walls (Lin et al. 2008).

Model Setup

Based on the 95-97 CIRP study used for model calibration and validation, the 3 month run went from Jul -Sep 96 and the 10 month from Jul 96 - Apr 97. All images and compiled bathymetry were chosen accordingly. Horizontal datum was State Plane Florida East, NAD83, metric and the vertical datum was NAVD88, metric. Digital Orthophoto Quarter Quadrangles (DOQQs) MrSID™ images were brought into SMS 10.1 and used to generate shoreline arcs within the map module. The 1 m resolution images were also used in ArcView 3.2® to verify coverage and location of the topographic data, as well as to generate geo-referenced polygon masks. Masks were used to clip the topographic data as needed and to facilitate comparison of net volume changes by sub-domain. The 1994 LIDAR was used for the nearshore region. The 1997 survey, with less along shore coverage, was cropped to cover the inlet proper. Offshore data was obtained from the Coastal Relief Model developed by NOAA's National Geophysical Data Center (NGDC). Data for the lagoon, bays, and Intercoastal Waterway were obtained from the St. John River Water Management District (SJRWMD). Beach profile surveys were obtained from the Florida Department of Environmental Protection (FDEP) for 1993 and 1997. All depths were made positive and horizontal conversion used USACE's Corpscon 6.0.

Each CMS model has its own Cartesian grid, with the wave model oriented + x onshore. SMS 10.1 allowed for duplication of the CMS-Flow grid and 180^{o} transformation; thus, generating identical grids except in cell numbering. Details of the grid design parameters are given in Figure 3. All CMS-Flow cells representing the inlet jetties were designated land (depth set to z = -2.24 m) and effectively removed from calculations. However, flow velocity calculations along these jettied/land cells included wall friction (Manning's coefficient of 0.025). For a jetty cell in CMS-Wave, the cell was assigned the "structure" attribute in order to model wave transmission and overtopping, as well as runup processes, associated with such features. The structure attribute was further designated as "rubble mound" with z = -2.24 m (emergent) and no other modifications.

CMS-Flow was driven by appropriate time series of WSE inserted at the three open boundaries and temporally-varying wind speed and direction added to the model control. Gaps were handled using MATLAB® and performing harmonic analyses (Pawlowicz et al. 2002) on the largest complete records, minimum of 45 days. All analyzed tidal constituents were then used to predict the missing data and a 31 hr low-pass signal from the closest tidal station was added to complete the record. CMS-Wave was forced each 3rd hr using a spectral energy grid generated from CHL Wave Information Studies (WIS) hindcast time series of wave height, period, and direction, as well as spreading parameters. Station 429 parameters (20 km offshore) were modeled in a larger domain (100 m x 100 m cell size), allowed to propagate shoreward, and results extracted at a center cell along the high resolution grid boundary. Spatially constant wind speed and direction were added at each time step.

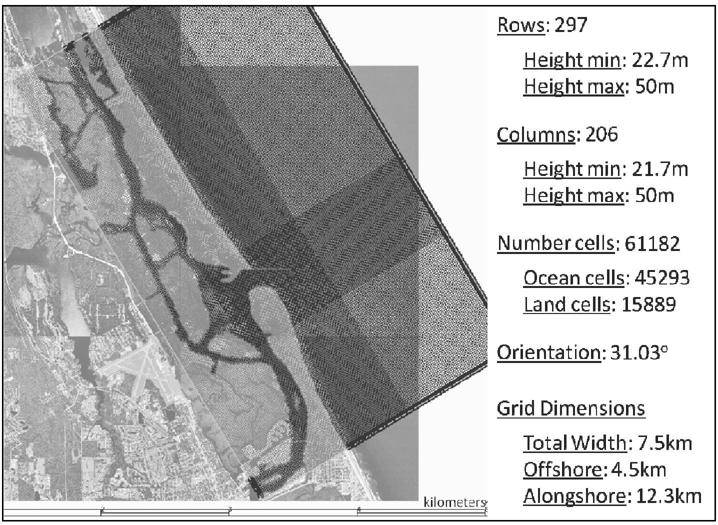

Figure 3. Design parameters for the CMS grids. (FDEP, 1999 DOQQ, original scale 1:12,000)

Model Control, Calibration, and Validation

The SMS interface provided the two-way coupling with water levels, currents, and updated bed level input into CMS-Wave every 3^{rd} hr. The updated wave parameters were returned to CMS-Flow at the end of each CMS-Wave run. The computation scheme begins with CMS-Wave, which runs for two intervals, repeating the initial forcing twice to achieve stability. Radiation stresses and breaking are then transferred to CMS-Flow which runs for three, 1 hr intervals calculating sediment transport and bed level change at each hour, following explicit calculation of the vertically-integrated equations of motion and continuity.

For CMS-Flow, the momentum equations included advection, mixing terms, and wall friction. The hydrodynamic time step was 1 s. The default Manning's coefficient of 0.025 was kept constant over the domain. The depth to begin drying cells was 0.01 m and the latitude of 28.5^{o} N was averaged over the domain. For sediment transport, inputs of WSE, currents, waves, and orbital velocities to the Lund-CIRP total load formula, with a transport rate time step of 20.0 s, returned hourly topographic updates. For CMS-Wave, wetting and drying was allowed and, as with the sediment transport, default parameters were chosen. The output files included radiation stresses and depth-limited spectral energy dissipation, based on the Extended Goda formula (Lin et al. 2008), which accounts for waves on opposing currents readily found at jettied inlets.

The model was calibrated (Jul to Sep '96) and validated (Oct 96 to Apr 97) by comparison of output WSE (eta) to the King et al. (1999) gauges and the Ponce Coast Guard Station tide gauge (8721147), see Figure 3 for gauge locations. Statistical analysis (Table 1) showed the average difference in eta for the ebb shoal during the 3 month calibration run was 11.6 cm, whereas the other three gauges showed minimal average offsets: 0.2 cm for the entrance to the inlet, 1.0 cm at the coast guard station inside the inlet, and 5.0 cm at the offshore gauge. For the 7 month validation run, the eta difference for the Coast Guard was 1.5 cm, while the Ebb Shoal was 38.1 cm. Given the Ebb Shoal gauge was mounted on the most dynamic sand body, with nominal depth and calibration based on the 1995 deployment, these results were acceptable. The root mean square deviation, normalized to the range of eta differences, showed variation of 3 to 11 cm for calibration. Time series plots (Figure 4) show the modeled eta (blue) was in phase with the measured (lime green) at all stations and times. Harmonic analysis also supports the model's performance in that the dominant tidal constituent, M2, matches in both amplitude (within 3 to 5 cm) and phase (within 2 to 4 degrees). Linear regression values during the longer validation period (not shown) ranged from an R^2 of 0.99 for the Coast Guard Station to 0.90 for the Ebb Shoal gauge.

Table 1. Statistical Analysis of Calibration and Validation Using WSE

GAUGE	AVG eta (meas-model) (m)	RMSD_24 (m)	Normalized RMSD_24 (m)	ABS Diff (m)
ebb	0.116	0.15	0.11	0.13
ent	0.002	0.08	0.06	0.07
off	0.050	0.10	0.08	0.09
coast	0.010	0.04	0.03	0.04
coastVal	0.015	0.04	0.08	0.04
ebbVal	0.381	0.41	0.35	0.38

GAUGE	Tidal amp M2 (m)		Tidal phase M2 (°)	
	Measured	Model	Measured	Model
ebb	0.58	0.52	307	311
ent	0.57	0.52	308	311
off	0.58	0.53	307	311
coast	0.47	0.44	326	324

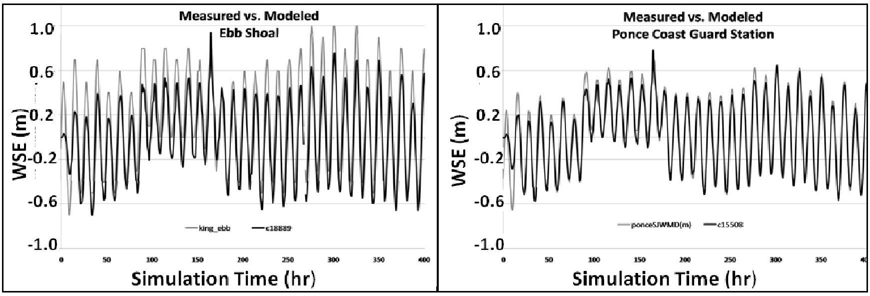

Figure 4. WSE for calibration at Ebb Shoal and Coast Guard: measured (lime) v. model (blue)

Design Alternatives

Based on the request for a parallel south jetty and observation of longshore transport reversals bringing sand back around the south jetty and into the inlet, all 15 design alternatives included a 300 m extension of the south jetty (SJ), removing the offset. In combination with the SJ were a variety of options and combinations: adding a 170 m rubble mound spur at 45° either emergent (SE) or submergent (SS), reopening the north weir (W), re-dredging the navigation channel (C) to its design location and depth (z = 4.6 m), dredging a deposition basin adjacent to the north jetty (B), that did or did not have an artificial rubble mound hard bottom (HB). If HB was done, so was C. All designs were run for 3 month predictions to determine their feasibility (Christian 2009). Only the most viable options were chosen for the long-term (10 month) modeling of fair weather, fall, and winter storms (Table 2) and are presented in this paper. Once the model was calibrated and validated with the present configuration, all design changes were based solely on individual cell depths (dredged) and cell attributes (hard bottom, jetty, submergent or emergent).

Results and Discussion

Analysis of each design's feasibility was addressed qualitatively by visual examination of a variety of contoured and vector plots: before and after morphology, net change morphology, and flow velocity (with and without morphology) during a spring and a neap tide. Feasibility was addressed quantitatively by volume change analysis within an area of interest using polygon masks (Figure 5) to represent both key areas of concern and key components of the inlet system. Each mask's net volume change was divided by starting volume of the mask for that design. These normalized net volumes were converted to percent to facilitate comparison of volume change within a mask among the design options.

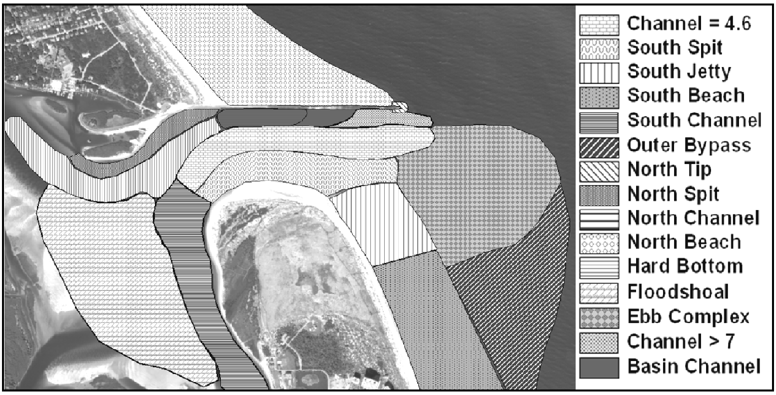

Figure 5. Schematic representing polygon masks used for volume analysis.

A major concern is shoaling of the South Spit. Volume changes (Table 2) show that all designs improve on the +22% increase observed in the Present configuration. Although the SJ/HB/SE design favorably shows a volume loss of -9.5% for the South Spit, this is due to shifting of the depositional area northward into the re-dredged navigation channel as observed in that net change plot (Figure 6). This shift was also observed for the SJ design, but produced a comparatively reduced volume gain of +13% given there was less erosion along the South Spit shoreline (Figure 7).

The design for an artificial bottom was to minimize the scour along the north jetty. All HB options remove this erosional pressure. The spur designs also show reduced scour of the Channel > 7 m mask next to the north jetty tip. However, the SJ/HB/SS comes with erosion/deposition (i.e. sand shifting shoreward) on the North Beach and North Jetty, whereas the south shoaling is an issue for SJ/HB/SE. Shifting of the North Beach sands to the shoreline may not be undesirable over a long period given the total volume change of +3.3% is still on par with the Present Design (+4.9%).

Table 2. Comparison of Normalized Volume Changes (%) for Long-term Runs (10 months)

Polygon Mask	Present	SJ	SJ/HB	SJ/HB/SE	SJ/SS/C	SJ/HB/SS
Ebb Complex	-8.62	-5.19	-6.19	-3.69	-3.48	-6.76
South Spit	21.54	12.57	14.65	-9.52	18.42	14.88
Channel = 4.6 m	-13.29	-14.14	-16.48	-7.82	-17.77	-17.88
Channel > 7 m	-20.58	-10.51	-6.07	3.83	-7.11	-2.04
Basin Channel	4.12	1.28	6.13	4.28	5.61	4.33
North Channel	3.32	3.32	3.28	3.40	1.50	1.41
South Jetty	-6.70	-11.25	-17.44	9.20	8.10	12.86
South Channel	-1.25	-1.09	-1.23	-2.09	-1.63	-1.19
South Beach	-5.13	-3.31	-1.37	3.76	-1.47	-0.88
Outer Bypass	7.76	5.77	7.57	4.58	4.09	4.11
North Tip	-51.35	-62.38	-57.14	-45.39	-62.34	-60.22
North Spit	0.26	-5.67	0.30	1.49	1.93	2.07
North Beach	4.85	3.94	3.60	-8.06	0.71	3.28
Hard Bottom	-2.47	-9.65	0.05	-3.28	-2.01	-2.68
Flood Shoal	-0.19	0.04	-2.17	0.92	-0.74	0.31

Bringing the navigation channel to its original design location and depth (z = 4.6 m) is beneficial as well. Shoaling of the South Spit is kept to the southern portion of the inlet oriented east-west rather than angling toward the channel, except for the SJ/HB/SE (Figure 6, bottom right). The shortened 4.5-month run of the SJ/C/SE should be investigated further given the promising results halfway into the run.

Although the SJ only redesign was the most likely alternative after 3 months, the final results of the long-term runs indicate the South Jetty Extension with Hard Bottom, Channel Redesign and Submerged Spur (SJ/HB/SS) may provide the best all-around relief from the navigation and shoaling concerns presently affecting Ponce de Leon Inlet, FL. This design shows minimal shoaling for the North Channel and continued scouring of all other navigation channels including Rockhouse Creek. Predicted volume losses to the South Beach are close to 0%, although an increase would be preferred. There is reduced deposition for the South Spit, despite the plethora of sand buildup along the updrift side of the south jetty just inside the inlet. Encroachment of the south spit shoal is still a concern, but could be remedied with a smaller HB area or reduced elevation of the submerged spur (i.e. more flow over it).

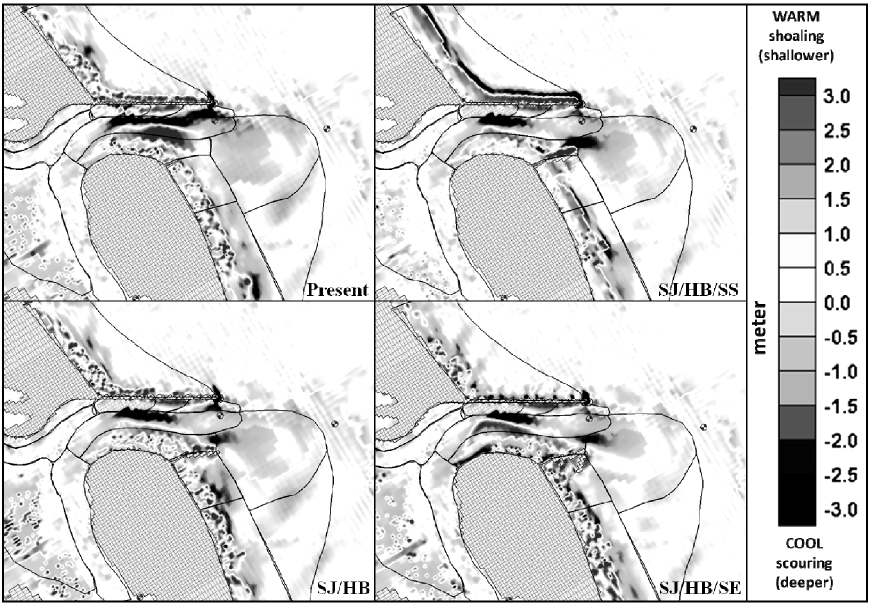

Figure 6. Comparison of net 10 month change in morphology for all South Jetty Extensions with HB and Channel Redesign. See text for acronyms.

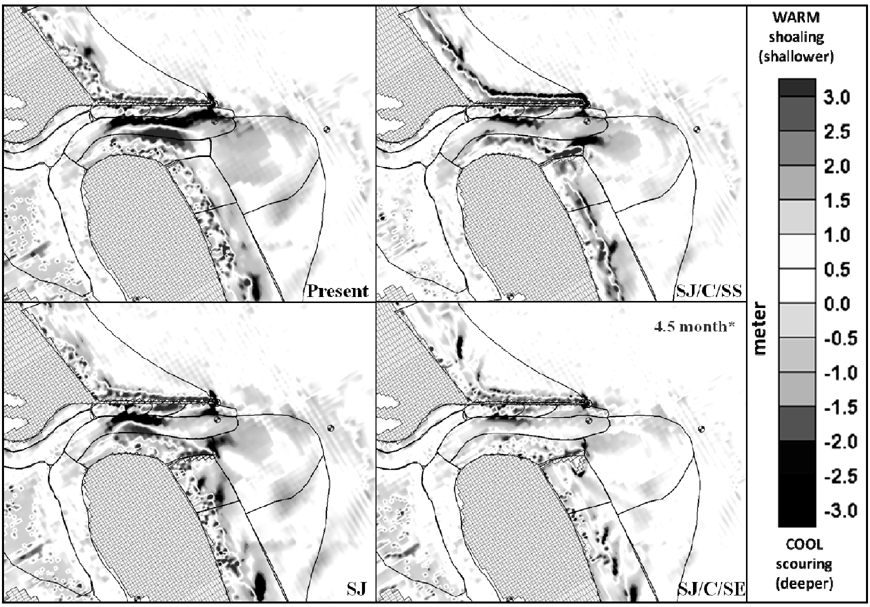

Figure 7. Comparison of net 10 month change in morphology for all South Jetty Extensions with no HB. See text for acronyms. *4.5 month run shortened due to technical issues.

Predicted neap tide flow for the SJ/HB/SS (Figure 9) shows reduction in maximum ebb and flood currents and the flow distributed across the inlet, in lieu of concentration in the northern extent as in the Present Design (Figure 8). Transport into the inlet from the south becomes efficient bypassing.

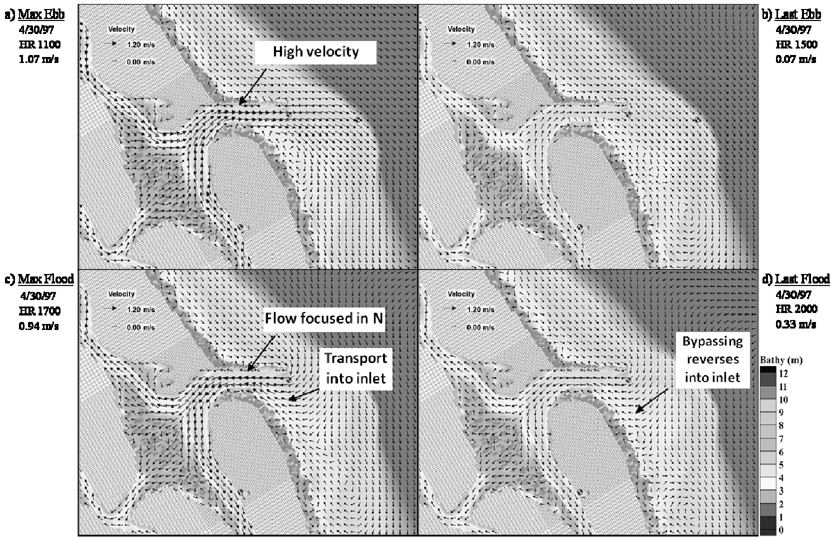

Figure 8. Morphology and flow velocities for Present Design during neap tide of 4/30/97.

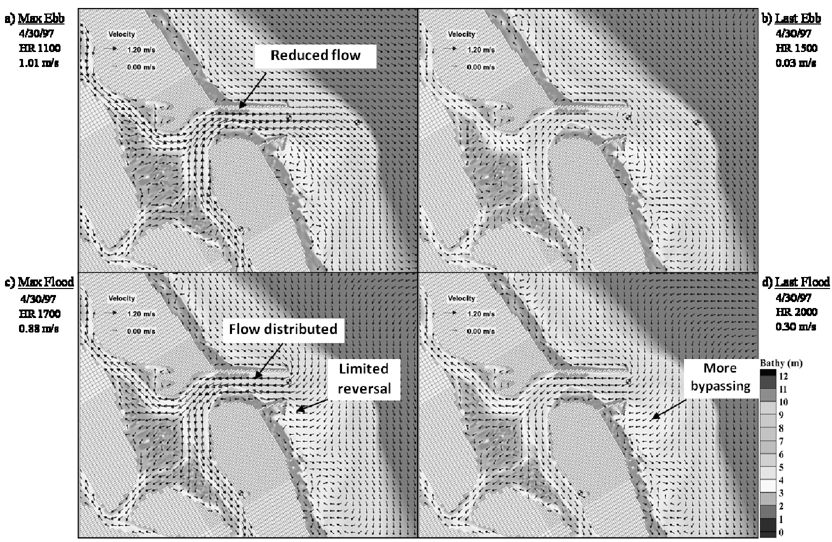

Figure 9. Morphology and flow velocities for SJ/ HB/SS during neap tide of 4/30/97.

Conclusions

The conclusions reached in this study serve to set the framework for redesigning Ponce de Leon Inlet, FL to improve three major areas of concern: severe shoaling of the south spit, mechanical stress on the north jetty structure caused by the shifted navigation channel, and hazardous passage along the navigation channel during high wave and wind events. The creation of an artificial hard bottom, by adding rubble mound into the deep and present location of the shifted navigation channel benefited the structural integrity of the north jetty by impeding the self-scouring of this area. The extension/channel/spur combinations showed that dredging the midline of the inlet to re-establish the location and depth of the original navigation channel had a positive effect on the self-scouring of that area and reduced the south spit shoaling keeping it limited to the southern half of the inlet. However, consideration was made to design for a smaller artificial hard bottom limited to the deepest parts of the shifted navigation channel that run closest to the north jetty.

Hydrodynamics of the present jetty configuration indicate an unequal distribution of flow across the inlet, with maximum currents favoring the northern half. This coincides with the erosional pressure and mechanical stress of the north jetty. Figure 8 shows how the Present Design's short south jetty easily allows flow into the inlet from the south bringing sand into the inlet and the flood flow moves directly from the ebb shoal to the throat. The SJ/HB/SS modification, which includes a redesign of the navigation channel into its original location and an artificial hard bottom basin at the base of the north jetty, shows vast improvement in the hydrodynamics. Predicted neap tide flow for this design shows reduction in maximum ebb and flood currents and flow being evenly distributed across the inlet. The rubble mound extension and spur interrupts transport into the inlet from the south, allowing the ebb shoal to be more efficient at bypassing.

Taken in total with the three areas of concern in mind, the South Jetty Extension with Submergent Spur, Hard Bottom, and Channel Redesign alternative (Figure 6, top right, and Figure 9) was determined to be the optimal candidate modeled in this study. Having established a protocol for analyzing the integrated hydrodynamic and morphologic modeling of Ponce de Leon Inlet, it is fair to say that a bit more work is required before the stalemate on engineering activities is lifted at this well-established inlet in need of modification. It is recommended to run a couple more alternatives and for an even longer period of, perhaps, two years. Analysis of the impacts on wave breaks based on the optimal candidates should also be addressed.

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References

Buttolph. A.M.; Reed, C.W.; Kraus, N.C.; Ono, N.; Larson, M.; Camenen, B.; Hanson, H.; Wamsley, T., and Zundel, A.K. (2006). "Two-dimensional depth-averaged circulation model CMS-M2D: Version 3, Report 2, Sediment transport and morphology change," *ERDC/CHL TR-06-09*, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Christian, P.J. (2009). "Ponce de Leon Inlet, FL: An integrated hydrodynamic and morphologic assessment of design alternatives using the U.S. Army Corps of Engineers' Coastal Modeling System," *Ph.D. Dissertation*, Department of Marine and Environmental Systems, Florida Institute of Technology, Melbourne, FL, 216p.

Demirbilek, Z., Lin, L., and Zundel, A. (2007). "WABED Model in the SMS: Part 2. Graphical Interface," *Technical Note ERDC/CHL CHETN-I-74*, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Harkins, G.S., Puckette, P., and Dorrell, C. (1997). "Physical model studies of Ponce de Leon Inlet, Florida," *Technical Report CHL-97-23*, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Howell, G.L. (1996). "A comprehensive field investigation of tidal inlet processes at Ponce de Leon Inlet, Florida," *Proceedings 25th International Conference on Coastal Engineering. Chapter 257*, Venice, Italy, ASCE Press, 295-307.

King, D.B., Smith, J.M., Militello, A., Stauble, D.K., and Waller, T.N. (1999). "Ponce de Leon Inlet, Florida, Site Investigation. Report 1, Selected Portions of Long-Term Measurements, 1995-1997," *Technical Report CHL-99-1*, U.S. Army Engineer Waterways Experiment Station, Coastal Hydraulics Laboratory, Vicksburg, MS.

Lin, L., Demirbilek, Z., Hajime, M., Zheng, J., and Yamada, F. (2008). "CMS-Wave: A nearshore spectral wave processes model for coastal inlets and navigation projects," *ERDC/CHL TR-08-13*, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Militello, A., Reed, C.W., Zundel, A.K., and Kraus, N.C. (2004). "Two-dimensional depth-averaged circulation model M2D: Version 2.0, Report 1: Documentation and user's guide," *ERDC/CHL TR-04-02*, U.S. Army Engineer Research and Development Center, Vicksburg, MS.

Pawlowicz, R., Beardsley, B., and Lentz, S. (2002). "Classical tidal harmonic analysis including error estimates in MATLAB using T_TIDE," *Computers and Geosciences*, 28, 929-937.

Srinivas, R. and Taylor, R.B. (1999). "Impacts of proposed improvements to Ponce de Leon Inlet, Florida," *Proceedings Coastal Sediments '99*, ASCE Press, 2265-2279.

Taylor, R.B.; Hull, T.J.; Srinivas, R., and Dompe, P.E. (1996a). *"Ponce de Leon Inlet Feasibility Study, Numerical Modeling and Shoaling Analysis, Volume I*," Taylor Engineering, Inc., Jacksonville, FL.

Taylor, R.B.; Hull, T.J.; Srinivas, R., and Dompe, P.E. (1996b). *"Ponce de Leon Inlet Feasibility Study, Numerical Modeling and Shoaling Analysis, Volume II,"* Taylor Engineering, Inc., Jacksonville, FL.

Zarillo, G.A. and Militello, A. (1999). "Ponce de Leon Inlet, Florida, Site Investigation. Report 2, Inlet Hydrodynamics: Monitoring and Interpretation of Physical Processes," *Technical Report CHL-99-1*, U.S. Army Engineer Waterways Experiment Station, Coastal Hydraulics Laboratory, Vicksburg, MS.